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CLIMATIC PROCESSES

Changes in the Duration of the Navigation Period in Arctic Seas along the Northern Sea Route in the Twenty-First Century: Bayesian Estimates Based on Calculations with the Ensemble of Climate Models

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Abstract—The duration of the navigation period (DNP) on the Northern Sea Route (NSR) and in some parts of it in the twenty-first century has been analyzed based on the models of the CMIP5 ensemble (Coupled Models Intercomparison project, phase 5) under the RCP 8.5 scenario using Bayesian averaging methods. According to the study results, differences in the quality of the DNP models and in DNP variations are greater in the western part of the NSR than in the eastern part. The DNP ensemble average was obtained in the range of 3–4 months in the middle of the twenty-first century and increasing to about six months by the end of the century. The ensemble average estimates of variations in DNP are generally robust for the choice of assumptions used for calculating the Bayesian weights. The joint consideration of the quality of modeled climate characteristics on all time scales (long-term average, interannual variations, and linear trend) in comparison with the satellite data makes it possible to reduce the intermodel standard deviation by two times for the western part of the NSR and one and a half times for the eastern part.

Keywords: sea ice, Northern Sea Route, CMIP5, Bayesian averaging, satellite data

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INTRODUCTION

The Arctic region is very sensitive to climate change. The warming velocity in the Arctic latitudes is several times higher than that in the global near-surface area in recent decades [1–3]. This warming is related to a rapid reduction in the sea ice area in the Arctic Ocean, especially in the summer and autumn seasons [2–4]. A significant decrease in the extent of sea ice in the Arctic basin in recent decades has resulted in a considerable increase in the duration of the navigation period (DNP) on the Northern Sea Route (NSR) [5–11].

The uncertain model estimates of future changes in the NSR parameters are due to the natural interannual variability, the accounting specifics of subgrid-scale processes in models, and the choice of scenarios for anthropogenic impacts on the Earth system. As a result, it is reasonable to apply the ensemble analysis of future climate changes using a large number of models, numerical experiments with such models when specifying different (but consistent with the available data on the pre-industrial climate status) initial integration conditions, and external impact scenarios. For example, some researchers [6, 7] select those climate models from the ensemble that realistically reproduce not only the present-day DNP on the NSR in comparison with the observational data, but also its velocity variations in recent decades. Others [8, 9] additionally require the adequate reproduction of standard deviations in the DNP interannual variability. In [11], the ensemble of model calculations using the Bayesian approach made it possible to obtain the estimated NSR changes in general with the analyzed interannual DNP variability along with long-term averages and estimated linear trends.

DATA AND RESEARCH METHODS

This paper reports the resulting analysis of DNP variations in different parts of the NSR based on numerical calculations with the ensemble of 25 CMIP5 climate models using the Bayesian approach [12].

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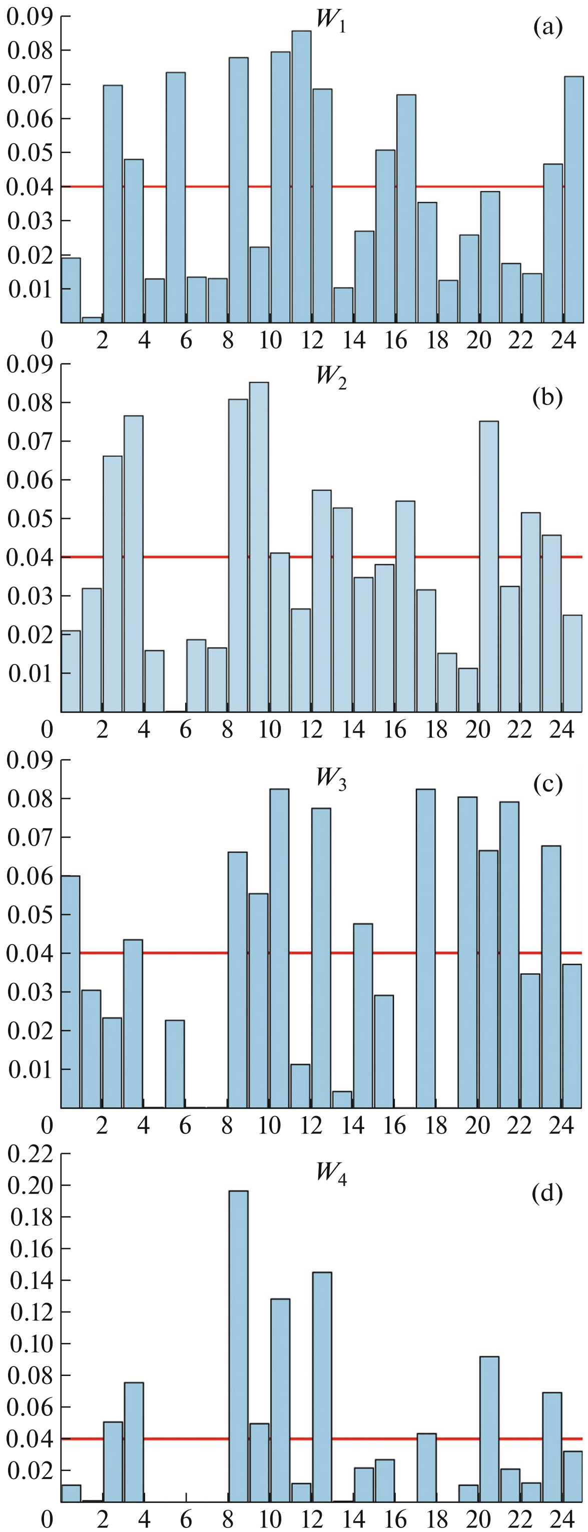

Fig. 1. Bayesian weights for 25 climate models (abscissa) determined in comparison with the satellite data on the period of 2006–2014 in the Barents and Kara seas: (a) W_1, (b) W_2, (c) W_3, (d) W_4. The horizontal line corresponds to $W_0 = 1/K$; $K = 25$ is the number of models in the ensemble.

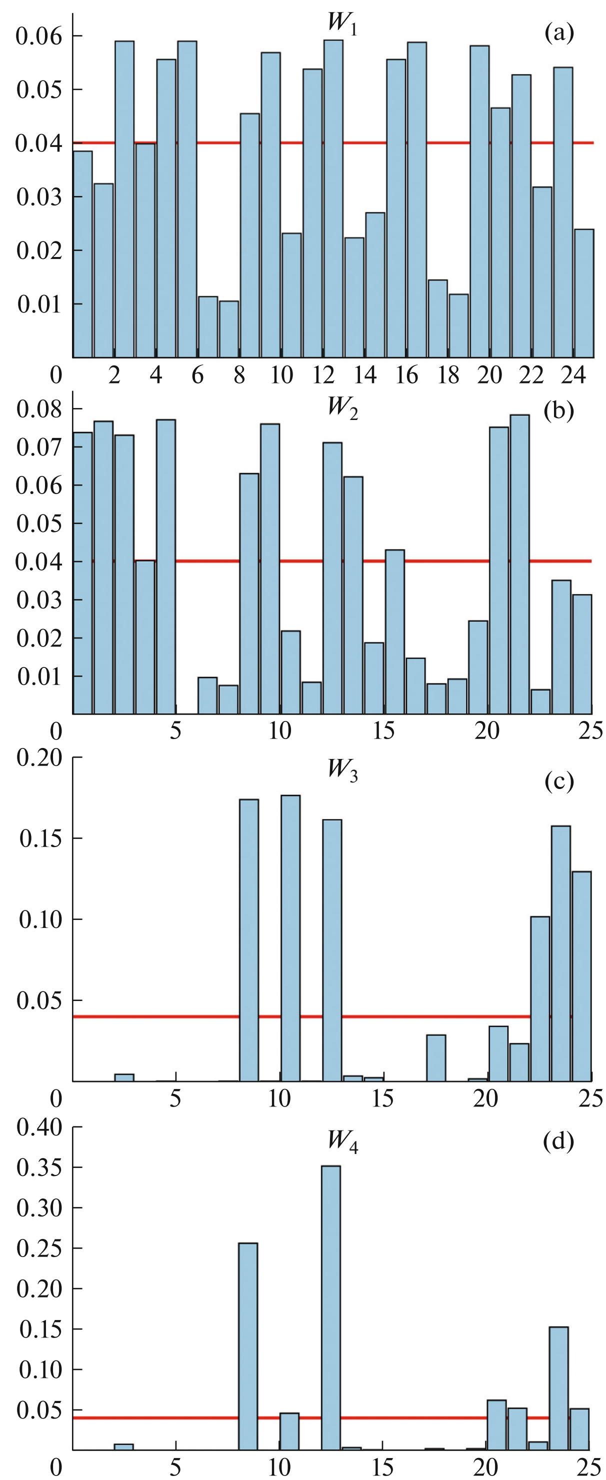

Fig. 2. Similar to Fig. 1 for the Laptev and East Siberian seas.

DATA AND RESEARCH METHODS

The analysis was carried out using numerical calculations of the sea ice concentration in the Arctic Ocean under the RCP 8.5 anthropogenic impact sce-

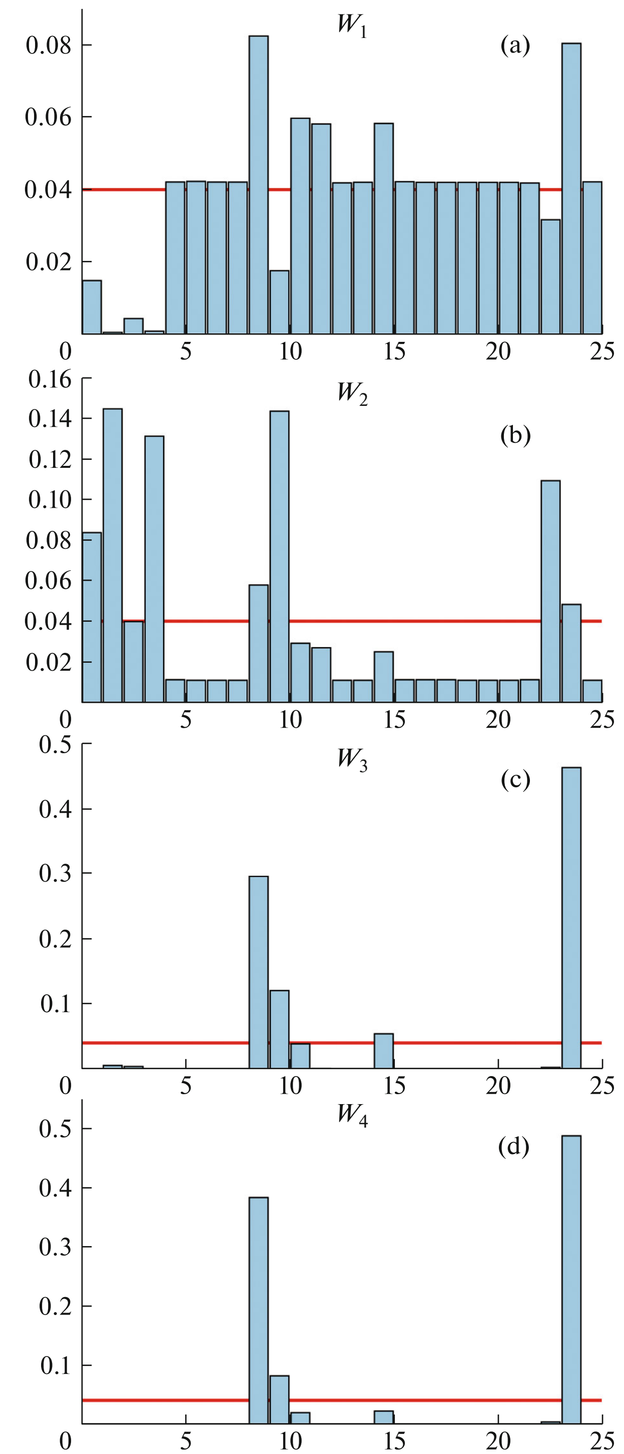

Fig. 3. Similar to Fig. 1 for the Vilkitskii Strait.

nario for the twenty-first century. The modeling quality was assessed based on the SMMR (Scanning Multichannel Microwave Radiometer) reference data on the Nimbus-7 satellite measurements for the period of 1980–2018 [13] (reference data D are shown below). To obtain more adequate quantitative estimates of the expected changes, we assessed the ability of climate models to reproduce the current features of sea ice distribution on the NSR, not only average values and trends, but also interannual variability.

The DNP changes were analyzed in different parts of the NSR on the basis of numerical calculations with the ensemble of 25 CMIP5 climate models. In this case, the Bayesian approach was used [14–18]. The analysis was carried out for the same ensemble of climate models and for the same NSR route as in [7], but with details for different parts of the NSR.

As in the earlier works [5–12] with the model-estimated DNP for the NSR in general, the water area was considered as free of sea ice when the ice concentration was less than 15%. In particular, the researchers of [11] determined the DNP upon the condition that at least 80% of the total NSR length was sea ice-free. This work was focused on the analysis of various parts of the NSR, including the western part of the NSR such as the Barents and Kara seas, the Vilkitskii Strait area, and the eastern part of the NSR such as the Laptev and East Siberian seas.

The navigation period duration $Y^{(k)}$ in each NSR area in the model k ($1 \le k \le K$; where the total number of models used is $K = 25$) was averaged with weights $w^{(k)}$ assessing the model reproduced DNP on the NSR for the ensemble average

$$E(Y|D) = \Sigma Y^{(k)} W^{(k)} \qquad (1)$$

and the intermodal standard deviation

$$\sigma(Y|D) = \Sigma\{[(\sigma^{(k)})^2 + Y^{(k)2}]W^{(k)} - E(Y|D)^2\}^{1/2}, \qquad (2)$$

where $\sigma^{(k)}$ is the interannual standard deviation of the Y variable calculated with the k model.

The Bayesian averaging weight factors were calculated as likelihood functions characterizing the model reproduction of DNP on the NSR $Y^{(k)}$ on different time scales, assuming a normal distribution of this variable on all time scales (abscissa):

$$W_i^{(k)} = \chi(Y^{(k)}; Y^{(D)}, \delta^{(D)}), \qquad (3)$$

where $\chi(y; y^{(D)}, \delta^{(D)})$ is the normal distribution of the variable y with an average $y^{(D)}$ and root-mean-square deviation $\delta^{(D)}$; the upper index (D) indicates the calculation based on the reference data, while the lower index i is the time scale. We calculated the long-term average $T_m^{(\cdot)}$ ($i = 1$ characterizes the time scale that is longer than the length I of the reference data D; in this case, the point is indicative either of the model number k or the reference data), the coefficient of the linear trend of this variable $\alpha_T^{(\cdot)}$ ($i = 2$ characterizes the interdecadal scale), and the root-mean-square deviation (RMSD) of interannual variability (IV) $\sigma_{T,IAV}^{(\cdot)}$ determined for the time series $Y^{(\cdot)}$ after exclusion of the

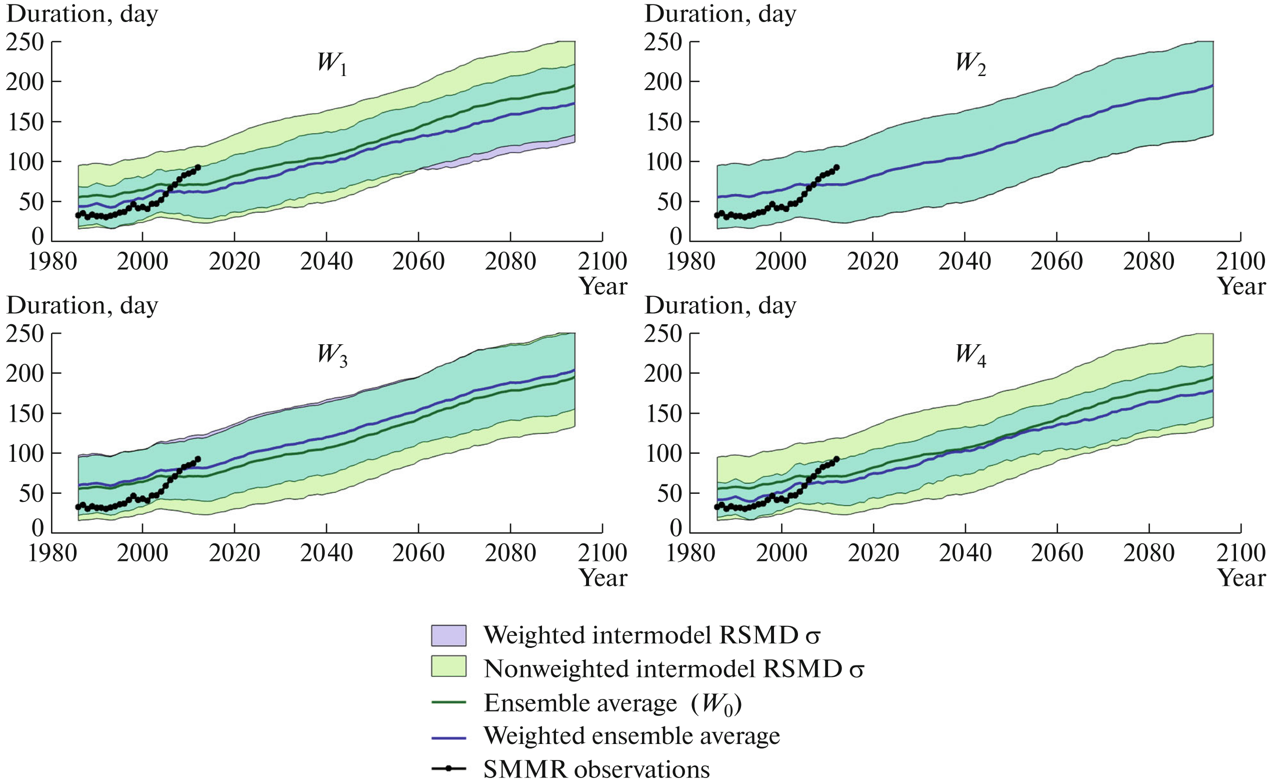

Fig. 4. Ensemble model estimates of changes in the duration of the navigation period along the Northern Sea Route for the Barents and Kara seas with different Bayesian calculation procedures W_j ($1 \leq j \leq 4$) compared to equally weighted (W_0) averaging of CMIP5 ensemble models.

linear trend with a coefficient $\alpha_T^{(\cdot)}$ ($i = 3$ characterizes the interannual scale). This approach was used in [11, 18]. $\sigma_{T,IAV}^{(\cdot)}$ was used as RSMD $\delta_i^{(\cdot)}$ for the long-term average ($i = 1$); for the linear trend coefficient ($i = 2$), the estimated RSMD of its sample estimate; for interannual RSMD ($i = 3$), $\theta \cdot \sigma_{T,IAV}^{(\cdot)}$ with $\theta = [2/(I-1)]^{1/4}$. The value θ estimates an uncertainty of $\sigma_{T,IAV}^{(\cdot)}$ for the time series with a finite length I [19]. $\theta \equiv 0.2$ was used in [11]. Differences in θ, in particular, in this work and in [11] lead to substantial differences in the weight distribution W_3.

We also considered the weights characterizing the overall quality of modeling the DNP on the NSR:

$$W_4^{(k)} = W_1^{(k)} W_2^{(k)} W_3^{(k)}. \tag{3}$$

Along with this, the normalization condition was used for all weights:

$$\Sigma_k W_j^{(k)} = 1 \quad (1 \leq j \leq 4). \tag{4}$$

The analysis was carried out for the same ensemble of climate models and for the same NSR route as in [6], but with details for different parts of the NSR.

RESULTS

Figures 1–3 show the Bayesian weights for the models (abscissa) determined in comparison with the satellite data for the period of 2006–2014. The models are in the best agreement with the observation data on the linear trend coefficient. In particular, the normalized information entropy

$$H_j = (\Sigma_k W_j^{(k)} \log_2 W_j^{(k)}) / \log_2 K \tag{5}$$

for weights W_2 is similar to one for all parts of the NSR; this fact is indicative of similar weights $W_1^{(k)}$ at different k. In the eastern part of the NSR (Laptev and East Siberian seas), the models are also in relatively good agreement with each other in relation to the long-term averages, so that the weight entropy W_1 for this section is 0.95. Meanwhile, H_1 is 0.83–0.86 in the western part of the NSR and in the Vilkitskii Strait, which is considerably different from one. The latter points to the different reproduction quality of DNP trends on the NSR in different models of the ensemble. As for weights characterizing the interannual scale, the H_3 entropy was obtained in the range from 0.94 to 0.98 for all parts of the NSR analyzed.

In the context of the combined weight W_4, the entropy is also the most similar to one (0.92) in the

Table 1. The duration of the navigation period (average and intra-ensemble standard deviations are in brackets) for different parts of the NSR depending on the Bayesian weight calculation procedure under the RCP 8.5 anthropogenic impact scenario for the twenty-first century

DNP (day)	Barents and Kara seas				
	W_0	W_1	W_2	W_3	W_4
2008–2028	79 (±50)	69 (±34)	79 (±50)	90 (±43)	71 (±30)
2040–2060	123 (±55)	115 (±39)	124 (±55)	136 (±44)	119 (±30)
2074–2094	181 (±60)	161 (±48)	182 (±58)	191 (±48)	166 (±35)
	Laptev and East Siberian seas				
2008–2028	55 (±35)	62 (±30)	55 (±35)	61 (±31)	65 (±26)
2040–2060	95 (±48)	105 (±43)	95 (±48)	104 (±39)	110 (±34)
2074–2094	151 (±56)	156 (±60)	151 (±56)	158 (±47)	162 (±47)
	Vilkitskii Strait				
2008–2028	37 (±47)	25 (±28)	37 (±47)	58 (±49)	36 (±27)
2040–2060	53 (±64)	49 (±49)	54 (±64)	83 (±64)	70 (±43)
2074–2094	77 (±92)	76 (±76)	77 (±92)	118 (±91)	106 (±66)

eastern part of the NSR. The corresponding modeling quality is worse in the western part of the NSR (H_4 = 0.79) and especially in the Vilkitskii Strait (H_4 = 0.74).

In the western part of the NSR (Barents and Kara seas), the ensemble average increases from 2–3 months in the first decades of the twenty-first century up to 4–4.5 months in the middle of the century, and up to about half a year at its end (Fig. 4; Table 1). Although the differences in ensemble averages for individual weights are formally not statistically significant (the difference between them does not exceed three weeks, whereas intra-ensemble Bayesian RSMDs range from a month to two months), their difference makes it pos-

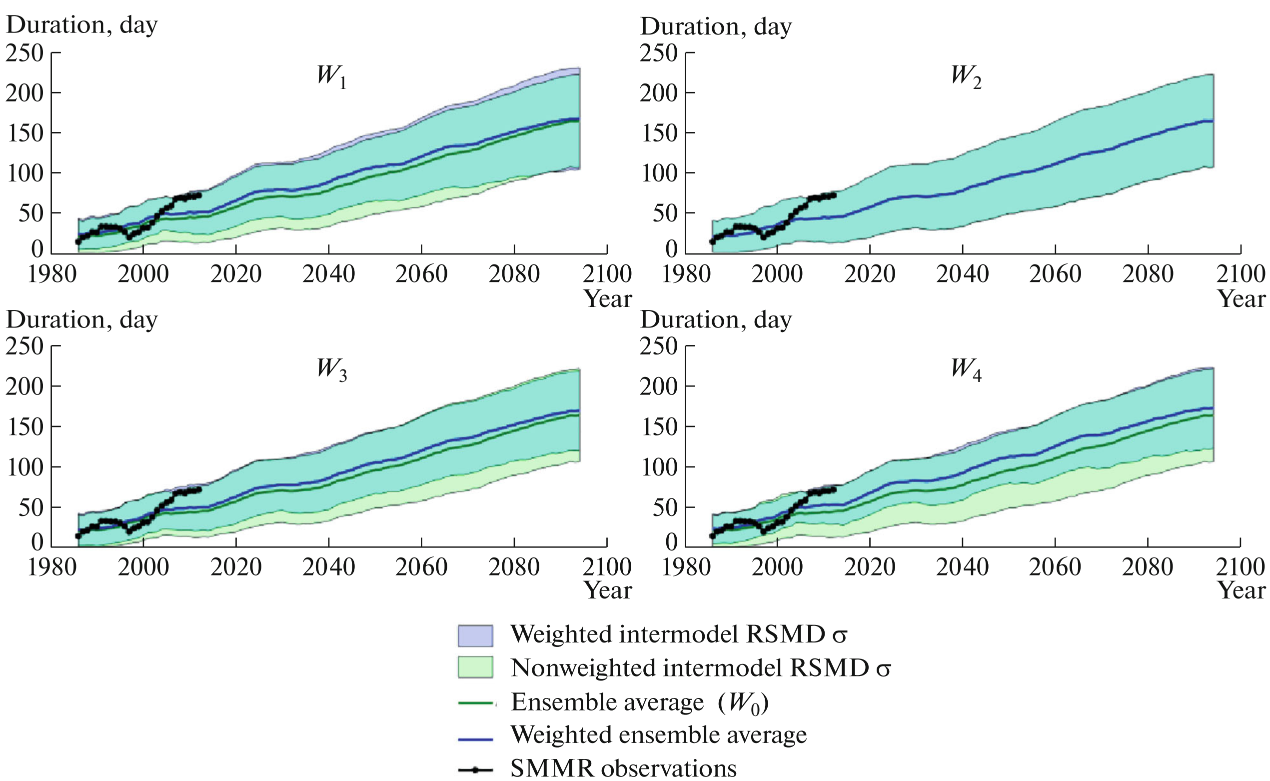

Fig. 5. Similar to Fig. 4 for the Laptev and East Siberian seas.

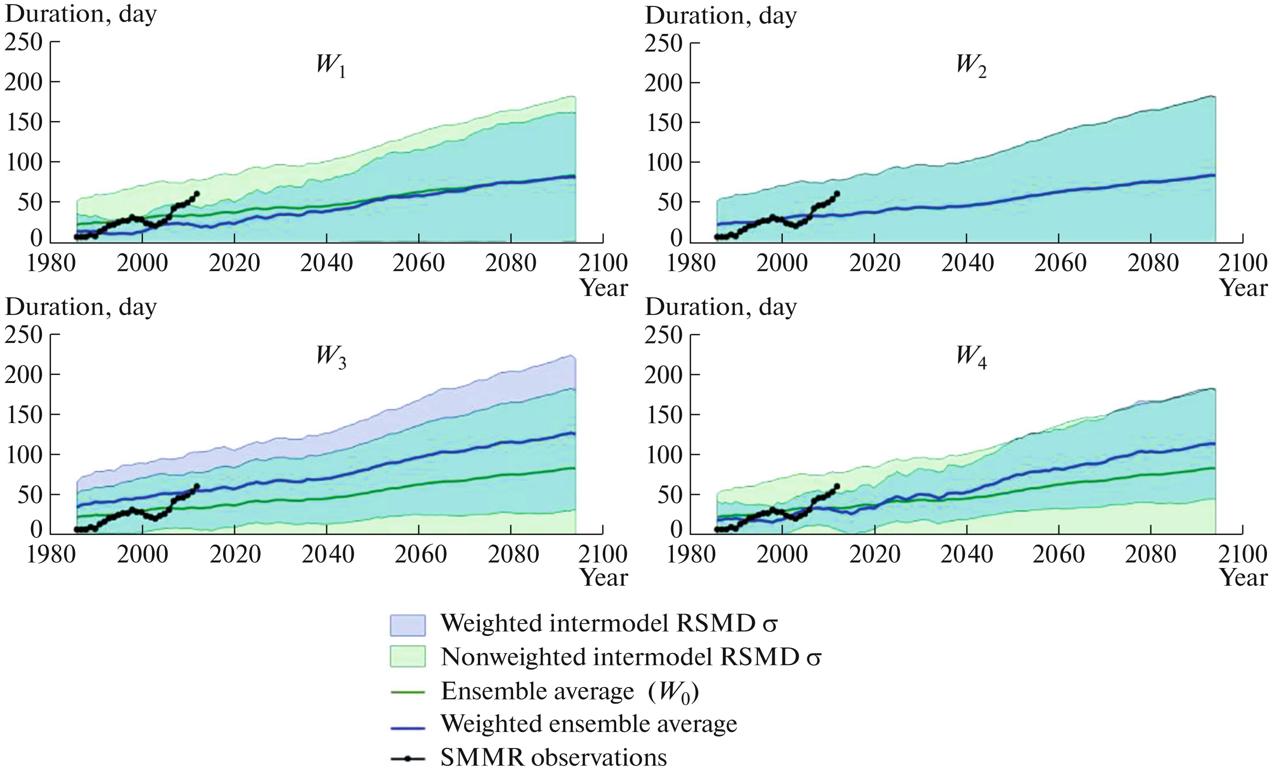

Fig. 6. Similar to Fig. 4 for the Vilkitskii Strait.

sible to analyze the influence of the Bayesian weight calculation procedure (a criterion for model selection within the ensemble) on the averaging results.

The minimum increase in DNP on the NSR was noted for W_1, which characterizes the long-term average (as well as for the combined W_4), and the maximum increase was noted for W_3, which characterizes the interannual variability in DNP. It should be noted that Bayesian averaging can almost halve the uncertainty in estimating DNP on the NSR, from 50–60 to 30–35 days, depending on the time interval with the combined weight W_4.

In the eastern part of the NSR (Laptev and East Siberian seas), the ensemble average DNP is close to two months in the first decades of the twenty-first century (Fig. 5; Table 1). It increases to 3–3.5 months by the middle of the twenty-first century and up to about five months by its end. Similar to that obtained for the western part of the NSR, the maximum increase in DNP was noted for the W_3 that characterizes the interannual variability. The minimum increase in DNP in this part of the NSR was noted for W_2, which characterizes a linear trend. In addition, similarly to that obtained for the Kara and Barents seas, Bayesian averaging reduces the estimation uncertainty by about a factor of 1.5, from 35–56 days up to 26–47 days, depending on the time interval at the combined weight W_4.

Differences in the ensemble averages for different Bayesian weight calculation procedures are much more significant for the Vilkitskii Strait than for the western and eastern parts of the NSR (Fig. 6; Table 1). For example, for the middle of the twenty-first century, the ensemble average DNP was obtained to be 49 (±49) days when using W_1 and 83 (±64) days when using W_3.

In general, according to the calculations with CMIP5 models under the RCP 8.5 scenario of external impacts on the Earth system, the ensemble average DNP is estimated at 3–4 months in the middle of the twenty-first century with an increase to about six months by the end of the century. The ensemble average estimates of variations in DNP are generally robust for the choice of assumptions involved in calculating the Bayesian weights.

CONCLUSIONS

The quality of modeling the DNP on the NSR and its changes is more different in the western part of the route than in the eastern part. The joint consideration of the quality of modeling the climate characteristics on all time scales (long-term average, interannual variations, and linear trend) in comparison with the satellite data makes it possible to reduce the intermodel standard deviation by half in the Russian Arctic seas.

The large intermodel scatter of DNP estimates in the Vilkitskii Strait is of particular interest.

The area of this strait is much smaller than the characteristic spatial resolution of the CMIP5 models [1]. In this regard, the Vilkitskii Strait is represented by a single computational grid cell in the models. In accordance with the Kotelnikov–Nyquist theorem, only variations in the spatial scale of at least twice the horizontal cell size of the computational grid can be resolved computationally. This fact limits the applicability of calculations with models of the Earth system and indicates the need to justify the use of models for estimating the future climate changes in regions with a relatively small spatial scale.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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